Rapid Cost Assessment of Space Mission Concepts through Application of Complexity-Based Cost Indices

Craig Peterson, James Cutts,
Tibor Balint, James B. Hall

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- Conclusions and future plans

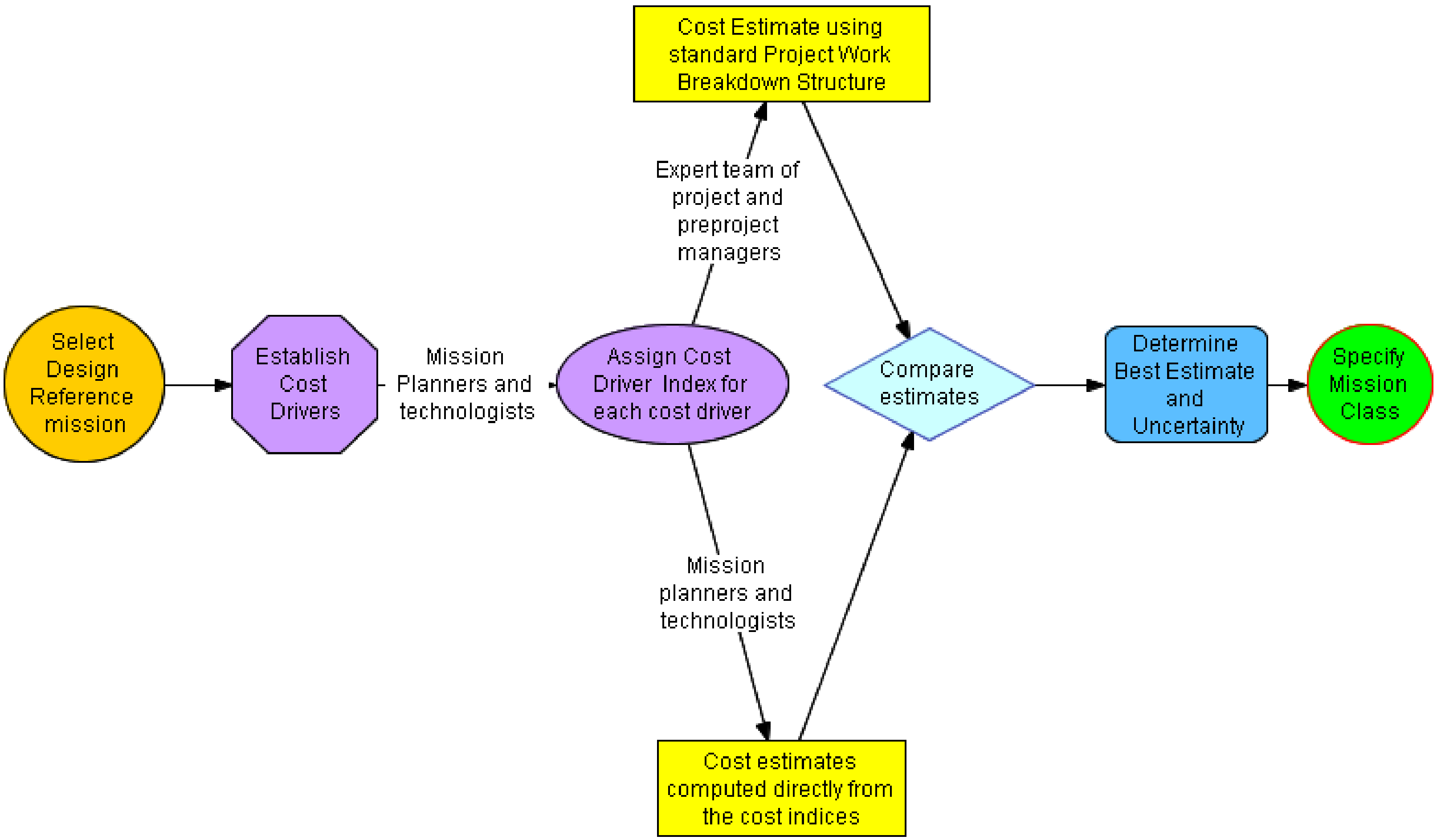
Introduction

- In Fall of 2004, NASA began developing 13 documents, known as "strategic roadmaps," intended to outline a strategy for space exploration over the next 30 years. The Third Strategic Roadmap, The Strategic Roadmap for Solar System Exploration, focused on strategy for robotic exploration of the Solar System.
- Development of the Strategic Roadmap for Solar System Exploration led to the investigation of a large variety of missions. However, the necessity of planning around scientific inquiry and budgetary constraints made it necessary for the roadmap development team to evaluate potential missions not only for scientific return but also cost.
- Performing detailed cost studies for each of the large number of missions was impractical given the time constraints involved and lack of detailed mission studies; so a method of rapid cost assessment was developed by us to allow preliminary analysis.
- Dave Bearden (Aerospace Corp.) and others have noted a strong correlation between complexity and cost and schedule of planetary missions. While these correlations were made after missions had been built and flown (successfully or otherwise), it seemed likely that a similar approach could provide at least some relative cost ranking.
- Cost estimation relationships (CERs) have been developed based on subsystem design choices. These CERs required more detailed information than available, forcing the team to adopt a more high level approach. Costing by analogy has been developed for small satellites, however, planetary exploration missions provide such varying spacecraft requirements that there is a lack of adequately comparable missions that can be used for analogy.

Introduction (cont'd.)

- This rapid cost assessment method facilitates analysis of mission costs without expending time and resources required for detailed cost studies.
- The rapid cost assessment approach makes use of cost/complexity ratings for key space mission technical and operational categories.
- Ratings provide numerical cost driver indices to create estimates of mission costs without exploring nuances of actual spacecraft design.
- Estimates can be used to develop funding profiles for programs of missions, initial analysis of mission and program chronology, including both program initiation and mission frequency.
- Rapid cost assessments made possible the efficient development of a long term expansive plan for Solar System exploration, as well as possible alternative scenarios in the face of funding changes.

Approach



Cost Estimate using standard Project Work Breakdown Structure
Expert team of project and preproject managers
Select Design Reference mission
Establish Cost Drivers
Mission Planners and technologists
Assign Cost Driver Index for each cost driver
Compare estimates
Determine Best Estimate and Uncertainty
Specify Mission Class
Mission planners and technologists
Cost estimates computed directly from the cost indices

Approach (cont'd.)

- The approach taken to develop the rapid cost assessment consisted of seven distinct steps, as follows:
  - 1. Select Mission
  - 2. Establish Cost Drivers
  - 3. Assign a cost index to each cost driver
  - 4. Compute costs based on cost index –or- obtain expert estimates from experienced managers
  - 5. Compare estimates and account for divergences
  - 6. Determine best estimate and uncertainty
  - 7. Assign mission class (Discovery, New Frontiers, Flagship)

Cost Drivers

- Cost drivers are the capabilities that the mission requires to complete its objectives.
- The rapid cost assessment made use of three primary cost driver categories:
  - launch operations,
  - flight systems, and
  - mission operations
- Four additional categories were also taken into account:
  - environment,
  - technology,
  - heritage, and
  - feed-forward
- These categories served to divide the mission into distinct, non-overlapping and comprehensive cost contributors, ensuring as many costs as possible were taken into account while eliminating the possibility of double counting.

Cost Driver Indices

- Associated with each cost driver is a cost driver index. The cost driver index is a proxy for the overall magnitude of the cost of a certain cost driver.
- Cost driver indices are assigned on a five level, exponential scale as follows:
  - Level 1 2 Points
  - Level 2 4 Points
  - Level 3 8 Points
  - Level 4 16 Points
  - Level 5 32 Points

Cost Driver Indices (cont'd.)

Cost Drivers/ Complexity Index	Level 1 (2)	Level 2 (4)	Level 3 (8)	Level 4 (16)	Level 5 (32)
Launch Vehicle					
Main Stage	Delta II with small fairing (2m) (could be too small for SSE)	Delta II with smaller fairing (3m)	Delta IV M or Atlas V with smaller fairing (4 - 5m)	Heavy launch vehicles: Delta IV-H or Atlas V with large fairing (5m)	Multiple Delta IV-H or Atlas V launches with in-orbit assembly
Launch approval		Launch approval for RTGs	Launch approval for RTG's and Earth Flyby		
Planetary Protection	Orbiter mission no new technology	Lander mission no new technology	Landed mission without RPS to Europa or special region on Mars	Landed mission with RPS or Europa or special region on Mars	Sample Return Mission from Europa
Flight systems					
Cruise Stage	Solar cruise stage inner planets	Solar cruise stage- to 5AU (LILT) - or - multiple probe carrier	Cruise stage to outer planet (>5AU) - or - RPS inside aeroshell		
Orbiter		Chemical propulsion	Chemical propulsion + Aerocapture (at Titan, Mars) or SEP	Orbit insertion at multiple satelites or large moons	Orbit insertion with aerocapture at Neptune
Entry or aeroassist system		Small probes to terrestrial planets	Large probes to Mars, Venus, Titan	Large probes to Outer Planets (Jupiter etc.)	Aeromaneuvering during entry OR outer planet probe
Descent and Landing		Dense atmosphere (Venus or Titan)	Airless body (Moon, Mercury, Europa) or balloon deployment near surface	Large lander with thin atmosphere or Outer Planets deep probes	
Planetary Mobility		Free flying aerobot (balloon)	Altitude control balloon or MER class rover	MSL class rover or fully controllable blimp	MSL class rover or blimp on Venus
Ascent vehicle - to upper atmosphere				From surface to 0.1 bar on Titan	From surface to 0.1 bar on Venus
Ascent vehicle- to orbit	Low g no atmosphere (moon), or asteroid	Moderate g - no atmosphere	Moderate g atmosphere (Titan and Mars)	Moderate g with "break-the-chain" Planetary Protection	Venus atmosphere (I.e., Earth-like and high g)
Rendezvous - capture			Artificial object - sample return canister	Natural object - asteroid or quiescent comet	Natural object - active comet
Earth Return Vehicle		No environmental control (Genesis or	Maintain cryogenic temperatures	Back Planetary Protection	
Science Payload	Simple - single instrument	Limited or 1 to 20 cm depth sampling	Moderate - 4 to 6 instrument or up to 2 m depth sampling	6 to 10 instrument or up to 100m depth sampling	Remote and in situ instruments or deep sampling (up to km)
Complexity (note: not duplicate units like 2 MERs)	One flight element	two flight elements	three fllight systems	four flight systems	five or more flight systems

Cost Driver Indices (cont'd.)

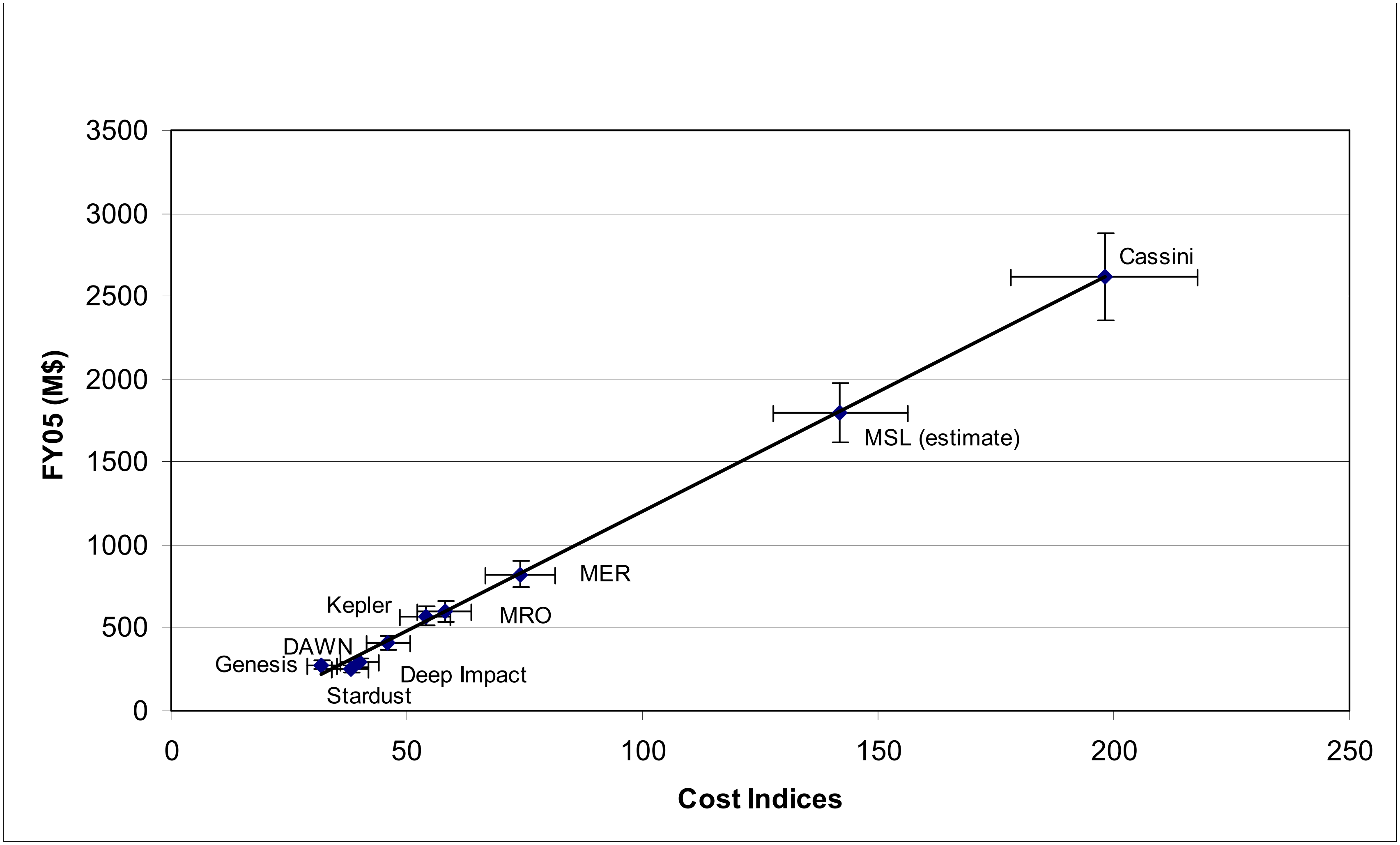
Cost Drivers/ Complexity Index	Level 1 (2)	Level 2 (4)	Level 3 (8)	Level 4 (16)	Level 5 (32)
Operations					
Lifetime	weeks (e.g. to Moon)	< 1 year - or - <1 week in Ext. Env	1 to 5 years - or - <6 months in Ext. Env	> 5 years - or - <1 year in Ext. Env	> 18 years (e.g. to KBO)- or - >1 year in Ext. Env
Science	PI led minimal science	Directed mission	Complex science operations		
Operations Complexity		Moderate	High	Extreme and/or novel	
Severe Environments					
Temperature	Low temperatures in vacuum	High temps in vacuum (Solar Probe) or low temps in atmosphere (Titan)	High Temps in atmosphere (Venus) or long duration at high temp vacuum (on Mercury)	High temps in atmopshere with long duration (on Venus)	
Pressure			Venus surface or Outer Planets Deep Probes (90-100 bar)	Extreme high pressure (Jupiter Deep Probes to 1000 bar)	
Radiation	< 0.6 AU or Jupiter Gravity Assist / flyby (10s of kRad)	Long duration mission or planetary magnetic field encounter (few 100 kRad)	Multiple passes through magnetic field (up to 500kRad to several MRad, e.g. Galileo)	Long duration operations inside magnetic field (10s of MRad, e.g., JIMO)	Long duration surface mission on Europa (multi-10s of MRad)
Other		far range (> 1km) comet dust particles, Mars surface dust	close range comet dust (<1 km), ring particles		
Technology					
Space System	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	One major mid TRL technology	One major low TRL system	Several low TRL systems
In Situ and Sample Return Systems	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	One major mid TRL technology	One major low TRL system	Several low TRL systems
Sensors and Instruments	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	One major mid TRL technology	One major low TRL system	Several low TRL systems
Autonomy	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	Limited autonomy but enabling	Sophisticated autonomy is enhancing	Sophisticated autonomy is enabling
Heritage	Nominally zero. Include an estimate as a NEGATIVE number if there is important heritage from prior mission				
Feedforward	Nominally zero. Include an estimate as a POSTIIVE number if mission incorporates features required for subsequent missions				

Cost Driver Indices (cont'd.)

	Mission Attributes		Primary Cost Drivers																	
			Launch ops			Flight Systems											Miss Ops			
Planned and Candidate Missions by Decade and Category	Category	Class	Main Stage	Launch Approv	Planetary Protect	Cruise Stage	Orbiter	Entry Descent	Descent & Landing	Mobility	Atmos ascent	Oribtal Ascent	Rendez-capture	ERV.	Science payload	Complexity	Lifetime	Complexity	Science	Sub-total Index
Reference Missions																				
Cassini	GP/LM	F	32	8	4		32		16						32	8	16	16	8	172
MER	MEP	B	4		4	2		8	8	8					4	4	4	4	4	54
Stardust	PB	D	4			4								4	4	2	8		2	28
Genesis	SEC	D	4			4								4	4	2	4	2	2	26
Deep Impact	PB	D	4			4		4							4	4	4	4	2	30
MRO	MEP	NF	4		2		4								16	2	8	4	4	44
DAWN	PB	D	4				8								4	2	16		2	36
Kepler	ASO	D	4												16	4	16	8	4	52
MSL (est.)	MEP	F	4	8	4	2		16	16	8					16	4	8	16	8	110

	Mission Attributes		Other Cost Drivers													
			Environments				Technology& Feed Forward									
Planned and Candidate Missions by Decade and Category	Category	Class	Extreme Temps	High Pressure	High Radiation	Other	Space Systems	Autonomy	In situ & S/Return	Science Sensors	Heritage	Feedforward	Other	Sub-total Index	Total Index	Actual Mission Cost FY05(M$)
Reference Missions																
Cassini	GP/LM	F	8	4	2		16	4		4			2	26	198	2619.7
MER	MEP	B				4	4	8	4	4	-4			20	74	824.5
Stardust	PB	D				4	2	2	4	2	-4			10	38	252.8
Genesis	SEC	D					2	2	4	2	-4			6	32	278.4
Deep Impact	PB	D				4	2	2	4	2	-4			10	40	289.5
MRO	MEP	NF					8	2	2	2				14	58	597.9
DAWN	PB	D					4	2				4		10	46	407.6
Kepler	ASO	D					2	2		2				6	58	571.6
MSL (est.)	MEP	F				4	8	4	4	4		8		32	142	1800.0

Cost Driver Indices (cont'd.)

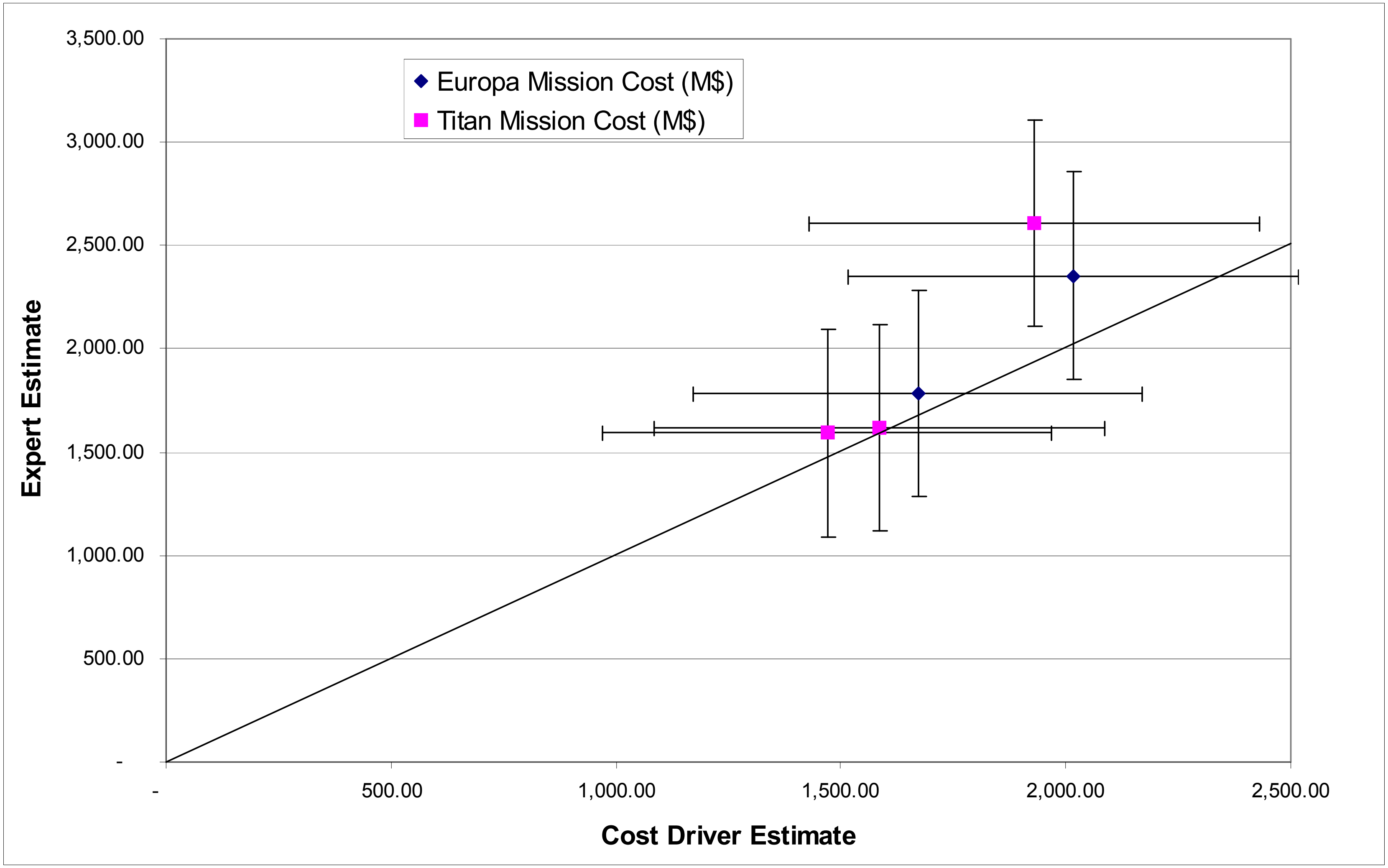


Cost Driver Comparison with Historic Mission Costs

Cost Estimation by Experts

- The expert team was given a briefing outlining mission objectives, desired capabilities, descriptions of the cost drivers and a set of possible mission profiles.
- Using the information from this briefing, the expert team compiled an estimate of mission costs based on their past experiences with the required mission attributes.
- Once these costs were evaluated, a method of applying standard wraps (percentages applied to spacecraft development or operational costs) was used to anticipate costs not directly estimated.
  - Wraps determine costs which do not fit into system attributes, such as project management during design and development or management reserves.
- The wraps and the expert team estimates were then added to determine the estimate of the total mission cost.
- The rapid cost assessment method was applied to five missions, three Titan missions and two Europa missions, in order to compare the results to those of the expert team.

Cost Estimation by Experts (cont'd.)



Comparison and Results

- Estimates generated by the mission cost indices were systemically lower than those generated by the expert team.
- Cost indices generated estimates that were ~10% lower than the expert estimates for lower complexity flagship missions and ~25% lower for high complexity missions.
- Because high complexity missions are inherently more difficult to categorize, this result was not unexpected.
- While the cost indices do make low estimates, they make consistently low estimates, and furthermore, the indices provided a fairly good approximation of the relative differences between mission options.

Conclusions and Future Plans

- While cost driver indices do not provide a substitute for detailed mission cost estimation, they do provide enough fidelity to be utilized during early planning stages of programs.
- Cost indices do appear to underestimate costs for missions at the high end of the mission cost range (>$2 billion)
  - Underestimation appears consistent and could be scaled appropriately
  - Further comparisons and analysis will likely prove that the simplified straight line fit is the cause of the underestimation, and an exponential curve fit may correct this
- The fidelity to relative differences between potential missions, suggests that even at this level, cost indices can be useful.
  - Their ability to rapidly determine an estimate that is both a reasonable approximation of potential mission costs and of the cost differences between missions can be used to determine appropriate mission categories (Discovery, New Frontiers, Scout, etc.) and develop different possible mission sets and possible overall program scheduling profiles.
  - In this way, cost driver indices do what they were designed to do.

Conclusions and Future Plans

- In order to build confidence in the estimation system, further validation against past missions and future mission studies will prove useful.
- While a fair number of missions were used in the development of cost indices, many more could be used in order to refine the model and assess any additionally needed categories.
- While the cost indices estimates for Europa and Titan were compared to the estimates of the expert teams, they have yet to be compared to detailed mission cost studies recently completed, which could provide deeper insight.
- In the meantime, mission cost indices provide a powerful tool for relative costing of missions needed for the development of future programs of space exploration.
- An automated (Excel-based) version of the estimation approach is currently being developed that will allow for even more rapid determination of estimates.

Craig Peterson *is Technologist for the Jet Propulsion Laboratory's Mission Systems Concepts Section, specializing in evaluating the benefits of potential new technologies for future mission concepts in support of NASA's Science Missions Directorate*

Tibor Balint *is a Senior Engineer at the Jet Propulsion Laboratory. His work within the Planetary and Lunar Missions Concepts Group involves programmatic support to NASA's Planetary Science Division, related to Solar System Exploration and to the Nuclear Systems and Technology Office related to RPSs*

James B. Hall *is currently studying for an MSc. in Mathematical Modeling and Scientific Computing at Oxford University, UK, where he works within the Oxford Center for Industrial and Applied Mathematics and the Computing Laboratory. He is a member of technical staff at The Aerospace Corporation where he works with the NASA/JPL Advanced Programs organization.*

James A. Cutts *is currently the Solar System Exploration Program Directorate Chief Technologist at JPL.*

Thanks for your attention